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Letter

Observation of the $J/\psi \to \mu^+\mu^-\mu^+\mu^-$ decay in proton-proton collisions at $\sqrt{s} = 13$ TeV

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The $J/\psi \to \mu^+\mu^-\mu^+\mu^-$ decay has been observed with a statistical significance in excess of five standard deviations. The analysis is based on an event sample of proton-proton collisions at a center-of-mass energy of 13 TeV, collected by the CMS experiment in 2018 and corresponding to an integrated luminosity of 33.6 fb^{-1}. Normalizing to the $J/\psi \to \mu^+\mu^-$ decay mode leads to a branching fraction of $[10.1^{+3.3}_{-2.7}(\mathrm{stat}) \pm 0.4(\mathrm{syst})] \times 10^{-7}$, a value that is consistent with the standard model prediction.

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Decays of particles to leptons, especially muons, provide some of the cleanest signatures at hadron collider experiments. The large data sample collected by the CMS experiment [1,2] at the CERN LHC offers an excellent opportunity to explore rare decays to multilepton final states. The first such observation was the decay of the Z boson into four leptons [3]. Subsequently, the decays $Z \to J/\psi \ell^+\ell^-$ (with the J/ψ decaying to two muons) and $\eta \to \mu^+\mu^-\mu^+\mu^-$ were also observed [4,5].

The BESIII collaboration recently reported the observation of the J/ψ decays $J/\psi \to e^+e^-e^+e^-$ and $J/\psi \to e^+e^-\mu^+\mu^-$, while for the $J/\psi \to \mu^+\mu^-\mu^+\mu^-$ branching fraction an upper limit was established, 1.6×10^{-6} at 90% confidence level [6]. In the standard model (SM), these processes occur via $\ell \to \ell\gamma^*/Z^*$ transitions, where the virtual photon or Z boson decays into a pair of leptons, as depicted in Fig. 1. These transitions provide opportunities to probe various beyond-SM scenarios, where new particles replace the γ^* or the Z^* boson [7–9]. Furthermore, such rare multilepton decays serve as a novel testing ground for quantum electrodynamics predictions [10,11].

This Letter presents the first observation of the $J/\psi \to \mu^+\mu^-\mu^+\mu^-$ decay and the measurement of its branching fraction, relative to the $J/\psi \to \mu^+\mu^-$ decay mode. The analysis is based on a sample of proton-proton collisions at a center-of-mass energy of 13 TeV, collected by the CMS experiment and corresponding to an integrated luminosity of 33.6 fb^{-1} [12].

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two end cap sections. Forward calorimeters extend the pseudorapidity (η) coverage provided by the barrel and end cap detectors. Muons are measured in the $|\eta| < 2.4$ range, with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive plate chambers. A more detailed description of the CMS detector can be found in Ref. [1].

Events of interest are selected using a two-tiered trigger system. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed latency of 4 μs [13]. The second level consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing and reduces the event rate before data storage [14].

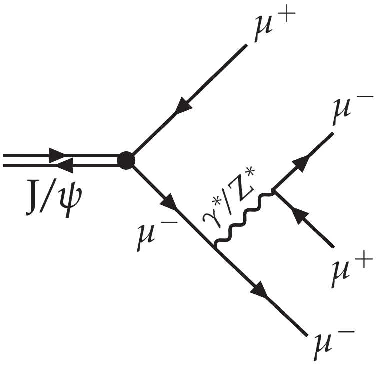

FIG. 1. Leading-order Feynman diagram representing the $J/\psi \to \mu^+\mu^-\mu^+\mu^-$ decay channel.

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The single-muon trigger efficiency exceeds 90% over the full η range, and the efficiency to reconstruct and identify muons is larger than 96%. By matching muons to tracks measured in the silicon tracker, the transverse momentum, p_{T}, is measured with a relative resolution of 1% in the barrel and 3% in the end caps, for muons with p_{T} up to 100 GeV [15].

This study exploits the "B parking" data sample collected by the CMS experiment in 2018 [16]. A specialized trigger and data storage strategy was implemented to assemble a dataset enriched in b hadron decays [17]. The trigger selects events with at least one muon with $p_{\mathrm{T}} > 9$ GeV and transverse impact parameter significance (distance of closest approach of the track to the beam line [18] divided by its uncertainty) larger than 6.

Two simulated event samples, used to evaluate the efficiency to reconstruct and select the $J/\psi \to \mu^+\mu^-\mu^+\mu^-$ and $J/\psi \to \mu^+\mu^-$ decays, are generated with the PYTHIA 8.230 Monte Carlo event generator [19], which includes modeling of the parton shower, fragmentation, and hadronization processes. The PYTHIA output is interfaced with EvtGen 1.3.0 [20], which simulates various b hadron decays. The samples are generated such that each event contains at least one b hadron decaying to a J/ψ meson plus other decay products, with the J/ψ meson decaying to either two or four muons using a phase space model. The underlying event is also modeled with PYTHIA 8, adopting the CP5 tune [21]. The NNPDF 3.1 [22] parton distribution functions are used. To account for additional proton-proton collisions in the same or adjacent bunch crossing (pileup), simulated minimum bias events are superimposed onto the hard scattering process, matching the multiplicity of reconstructed vertices observed in collision data. Final-state photon radiation is simulated using PHOTOS 3.61 [23]. The response of the CMS detector is emulated using Geant4 [24]. The simulated event samples are reconstructed using the same software packages as employed for collision data.

The events selected by the trigger need to comply with additional selection criteria, including the presence of four reconstructed muons with a net charge of zero and an invariant mass in the $2.6 < m_{\mu^+\mu^-\mu^+\mu^-} < 3.4$ GeV range. All the four selected muons are required to have $|\eta| < 1.5$ and $p_{\mathrm{T}} > 3.5$ GeV. One of them must match the muon that triggered the event, which is ensured by requiring that it has $p_{\mathrm{T}} > 9$ GeV and a small angular distance with respect to the trigger muon, $\sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.1$, where $\Delta\eta$ and $\Delta\phi$ are the differences in pseudorapidity and azimuthal angle, respectively.

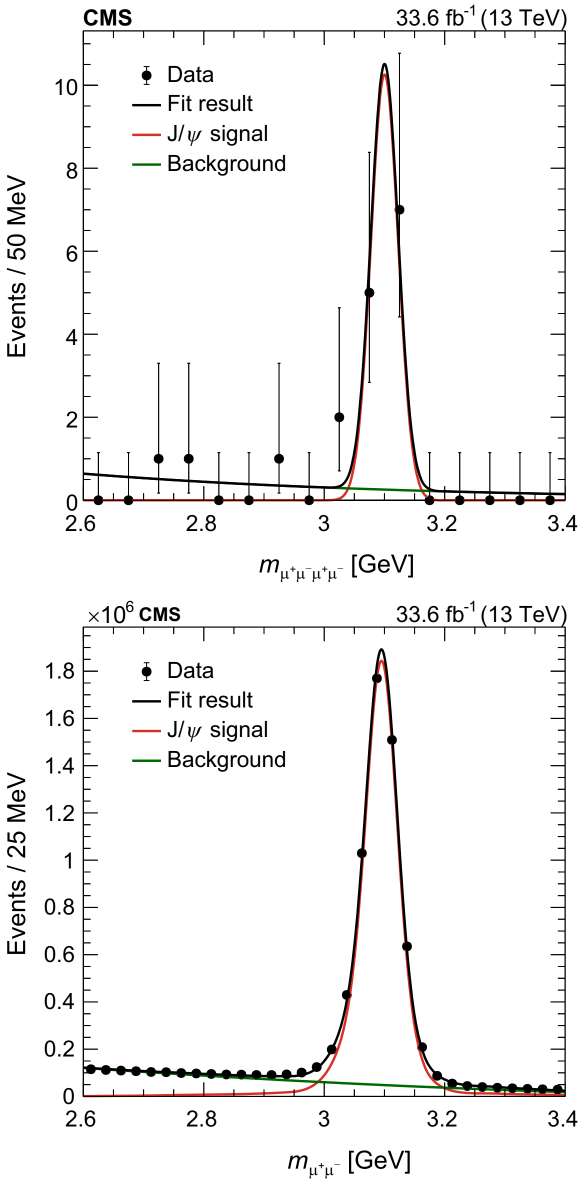

FIG. 2. Measured four-muon (left) and dimuon (right) mass distributions. The vertical bars represent the statistical uncertainties. The solid black line represents the result of the unbinned fit described in the text, while the red and green lines represent the signal and background terms, respectively.

The four muons forming a J/ψ candidate are fitted to a common vertex, determined by a Kalman filter vertex fit [25]. Only candidates with a vertex-fit χ^2 probability exceeding 1% are kept. The p_{T} of the J/ψ meson candidate must exceed 25 GeV and its absolute rapidity is restricted to be less than 2.2. No oppositely charged muon pair combination can have an invariant mass in the 0.75–0.80 or 0.98–1.05 GeV ranges, which are populated by dimuon decays of the ρ, ω, and ϕ mesons.

The branching fraction of the $J/\psi \to \mu^+\mu^-\mu^+\mu^-$ decay mode is measured relative to that of the $J/\psi \to \mu^+\mu^-$ decay. The selection criteria used in the $J/\psi \to \mu^+\mu^-$

events are the same as those applied to the two highest p_{T} muons of the $J/\psi \to \mu^+\mu^-\mu^+\mu^-$ decay.

Unbinned maximum likelihood fits are performed on the four-muon and dimuon invariant mass distributions to determine the two signal yields. The $\mu^+\mu^-\mu^+\mu^-$ invariant mass distribution is fitted by the superposition of two functions, one representing the $J/\psi \to \mu^+\mu^-\mu^+\mu^-$ signal and the other the underlying continuum background. The signal is modeled by a Crystal Ball function [26], with the mean fixed to the world-average J/ψ meson mass [27] and the width and tail parameters fixed to values determined from studies of simulated events. The background is modeled by a linear function. The $\mu^+\mu^-$ invariant mass distribution is fitted with essentially the same fit model, except that the signal is represented by the sum of a Crystal Ball function and a Gaussian function, without constraining any of the parameters. The fit models do not include peaking background terms from hadronic J/ψ decay modes because the probability that a pion reaches the muon stations and is misidentified as a muon is below the per mil level [15], so that such contributions are negligible. The measured $m_{\mu^+\mu^-\mu^+\mu^-}$ and $m_{\mu^+\mu^-}$ distributions are shown in Fig. 2, together with the results of the fits.

The yields returned by the fits are $N(J/\psi \to \mu^+\mu^-\mu^+\mu^-) = 11.6^{+3.8}_{-3.1}$ and $N(J/\psi \to \mu^+\mu^-) = (5770 \pm 3) \times 10^3$. The significance of the $J/\psi \to \mu^+\mu^-\mu^+\mu^-$ signal is above 7 standard deviations, evaluated from the likelihood ratio of the default signal-plus-background fit and the background-only fit, imposing $N(J/\psi \to \mu^+\mu^-\mu^+\mu^-) = 0$, using the standard asymptotic formula [28].

The $J/\psi \to \mu^+\mu^-\mu^+\mu^-$ branching fraction relative to that of the $J/\psi \to \mu^+\mu^-$ is computed as

$$\frac{\mathcal{B}(J/\psi \to \mu^+\mu^-\mu^+\mu^-)}{\mathcal{B}(J/\psi \to \mu^+\mu^-)} = \frac{N(J/\psi \to \mu^+\mu^-\mu^+\mu^-)}{N(J/\psi \to \mu^+\mu^-)} \Bigg/ \frac{\epsilon_{J/\psi\to\mu^+\mu^-\mu^+\mu^-}}{\epsilon_{J/\psi\to\mu^+\mu^-}}, \qquad (1)$$

where $\mathcal{B}(J/\psi \to \mu^+\mu^-)$ is the branching fraction of the reference channel. The reconstruction efficiencies of each process are calculated as the fractions of generated events that are reconstructed, their ratio being $\epsilon_{J/\psi\to\mu^+\mu^-\mu^+\mu^-}/\epsilon_{J/\psi\to\mu^+\mu^-} = (11.92 \pm 0.02)\%$, where the uncertainty reflects the size of the simulated samples.

Because the signal- and reference-channel events are recorded using the same trigger and share similar event topologies, many systematic uncertainties have been seen to cancel in Eq. (1). In the following, we only describe those that do not cancel.

We evaluate the sensitivity of $N(J/\psi \to \mu^+\mu^-\mu^+\mu^-)$ to the fit model by replacing the Crystal Ball function by a Gaussian function and the linear function by an exponential function. The corresponding systematic uncertainties are smaller than 0.1% when we replace the signal fit model and 0.4% when we replace the background model. For the alternative modeling of the reference channel we use a sum of two Crystal Ball functions for the signal and an exponential function for the background. The fitted value of $N(J/\psi \to \mu^+\mu^-)$ changes by 0.5% for each of the two variations. An additional 0.1% uncertainty reflects the size of the Monte Carlo samples used for calculating the reconstruction and selection efficiencies of the signal and reference channels. Differences between the reconstructed and simulated samples are accounted for through two scale factors, one reflecting the trigger efficiency and the other the reconstruction and event selection efficiencies. Varying these scale factors by their standard deviation uncertainties, we obtain the corresponding uncertainties on the branching fraction measurement: 1.9% and 1.4%, respectively. Recomputing the detection efficiencies with conservative variations of the simulated J/ψ kinematical distributions leads to a systematic uncertainty of 2.8%. The total relative systematic uncertainty is 3.7%, computed as the quadratic sum of the individual terms, so that the final result is

$$\frac{\mathcal{B}(J/\psi \to \mu^+\mu^-\mu^+\mu^-)}{\mathcal{B}(J/\psi \to \mu^+\mu^-)} = [16.9^{+5.5}_{-4.6}(\mathrm{stat}) \pm 0.6(\mathrm{syst})] \times 10^{-6}.$$

Using the world's average $\mathcal{B}(J/\psi \to \mu^+\mu^-) = (5.961 \pm 0.033)\%$ [27], and propagating its uncertainty, we obtain

$$\mathcal{B}(J/\psi \to \mu^+\mu^-\mu^+\mu^-) = [10.1^{+3.3}_{-2.7}(\mathrm{stat}) \pm 0.4(\mathrm{syst})] \times 10^{-7},$$

a value consistent with the SM prediction, $(9.74 \pm 0.05) \times 10^{-7}$ [10].

The results reported in this paper are tabulated in the HEPData record for this analysis [29].

In summary, using a data sample of proton-proton collisions at $\sqrt{s} = 13$ TeV, collected in 2018 by the CMS collaboration and corresponding to an integrated luminosity of 33.6 fb^{-1}, the $J/\psi \to \mu^+\mu^-\mu^+\mu^-$ decay was observed for the first time, with a statistical significance exceeding five standard deviations. Taking the $J/\psi \to \mu^+\mu^-$ decay mode as normalization, its branching fraction was measured to be $\mathcal{B}(J/\psi \to \mu^+\mu^-\mu^+\mu^-) = [10.1^{+3.3}_{-2.7}(\mathrm{stat}) \pm 0.4(\mathrm{syst})] \times 10^{-7}$, a value consistent with the standard model prediction.

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